CHAPTER 8

PRINCIPLES FOR THE DESIGN OF FOUNDATIONS

8.1 INTRODUCTION

The engineer is presumed to understand all of the methods presented here and to be able to make an appropriate decision about their applicability. What other things are necessary in developing a design? This chapter addresses that question.

The first section is closely related to the principles that must be employed in the design of foundations. To be an engineer is to be a member of a profession that has made innumerable contributions to the betterment of human life. The goal of an engineer is to act so as to add to such contributions.

8.2 STANDARDS OF PROFESSIONAL CONDUCT

Perhaps the most valuable characteristic of the engineer is integrity. The client expects the engineer to approach the proposed project with careful attention and relevant knowledge based on education and experience. The client understands that the engineer will comply fully with the standards of professional conduct set forth by the American Society of Civil Engineers (ASCE, 2000). The fundamental principles and the fundamental canons abstracted from the ASCE document are shown below.

8.2.1 Fundamental Principles

Engineers uphold and advance the integrity, honor, and dignity of the engineering profession by:

1. Using their knowledge and skill for the enhancement of human welfare and the environment;
2. Being honest and impartial and serving with fidelity the public, their employees, and clients;
3. Striving to increase the competence and prestige of the engineering profession; and
4. Supporting the professional and technical societies of their disciplines.

8.2.2 Fundamental Canons

1. Engineers shall hold paramount the safety, health, and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties.
2. Engineers shall perform services only in the areas of their competence.
3. Engineers shall issue public statements only in an objective and truthful manner.
4. Engineers shall act in professional matters for each employer or client as faithful agents or trustees, and shall avoid conflicts of interest.
5. Engineers shall build their professional reputation on the merit of their services and shall not compete unfairly with others.
6. Engineers shall act in such manner as to uphold and enhance the honor, integrity, and dignity of the engineering profession.
7. Engineers shall continue their professional development throughout their careers and shall provide opportunities for the professional development of those engineers under their supervision.

These 11 statements from ASCE are worthy of being framed and hung on the walls of university classrooms and engineering offices.

8.3 DESIGN TEAM

The geotechnical engineer becomes a member of the design team, where the owner and the architect provide information on the aims of the project, on special requirements, on an expected date for completion of construction, and on any requirements of governmental agencies with jurisdiction at the site. The structural engineer and other engineers are also members of the team. The team will be organized differently if a design-build contract is to be used.

A close working arrangement is developed between the geotechnical engineer and the structural engineer. As noted throughout this book, a number of problems must be solved that involve structural engineering, and the structural engineer may be the lead designer. However, the participation of the

geotechnical engineer should continue through construction, and not end with the submission of *p-y* curves, *t-z* curves, and similar information. Questions to be answered by the geotechnical engineer will normally arise throughout the period of design and construction.

8.4 CODES AND STANDARDS

The governmental agency in the area where the project is located will specify a building code. Many agencies will specify a code such as the *Uniform Building Code* or the *Southern Building Code.* Some states, such as Florida and Oregon, have prepared their own building codes, as have some large cities, such as New York City. If the project is a bridge or another highway structure, most states have prepared specifications for highway construction, such as Standard Specifications, for the Department of Transportation of the State of California.

Many of the codes are silent on aspects of the design of foundations, but the engineer will study carefully any provisions that are given to prevent a violation. Most of the *Uniform Building Code* (1991 edition) contains requirements for the architect. Part V is entitled Engineering Regulations—Quality and the Design of Materials of Construction, and Part VI, Detailed Regulations, includes Chapter 29, Excavations, Foundations and Retaining Walls.

Detailed procedures for certain engineering operations have been written by professional societies, such as the ASTM. The ASTM standards are referenced extensively in Chapter 4, and the engineer will use them where appropriate.

8.5 DETAILS OF THE PROJECT

The engineer will develop a clear view of the nature of the project, whether a monumental structure for the ages or a temporary warehouse. The details of the design will, of course, vary with the project. Two types of failure can be identified with respect to the foundation: (1) failure due to excessive cost and (2) collapse of the structure. The first failure can be eliminated by careful work, by employing appropriate methods, and by using an appropriate factor of safety.

The results of a collapse need to be considered. Will the collapse be catastrophic, with loss of life, or will a large monetary loss be incurred or only a small one? While each possibility needs consideration, the collapse of even a minor structure should be avoided.

On occasion, what is thought to be a collapse is only excessive settlement. A theme of this book is computation of the movement of the foundation under

any load. Therefore, with regard to all elements of the project being addressed, the engineer will require knowledge of the tolerance to total settlement and to differential settlement.

Determination of the loads to be employed in designing the foundation of a structure is sometimes no simple matter. The design of the foundations for an overhead sign depends on maximum wind velocity, which is a statistical problem. The pattern of the velocity with time is also important, no data may be available for use in the design. The loads to be used in designing the piles for an offshore platform are related to the maximum waves that will develop from a storm. Prediction of the maximum storm that will occur at some location in the ocean during the life of a structure is based on data from that area of the ocean, and such data may be scarce or nonexistent.

Professor Ralph Peck (1967) made some observations about the criteria for the design of a structure. He noted that the floor load was based on the weight of the goods to be stacked to a given height in a warehouse but the load on the foundations was computed by assuming that the entire of the warehouse floor was covered; however, the use of the warehouse required numerous aisles throughout the building. Another example given by Professor Peck was that a certain rotating machine had bearings whose differential movement could be only a small fraction of an inch. However, that same machine was used on a ship that rolled with the waves!

8.6 FACTOR OF SAFETY

A comprehensive discussion of factor of safety involves a multitude of factors. Only a brief presentation is given here to emphasize the importance of this topic in the design process. First, the engineer must refer to the building code covering the project for a list of requirements. Many building codes give some discretion to the engineer, depending on the details of the design.

Next, the engineer must make a study to determine the quality of the data related to the design. The loads to be sustained by the foundation were noted above. In many cases, the loads and tolerance to settlement will change as the design of the superstructure proceeds. The subsurface investigation was discussed in Chapter 4, and many factors can affect the quality of the information on the soil available for the design. If piles are to be used to support the structure, the engineer must examine carefully the available data on the results of load tests on the type of pile to be used in soils similar to those at the site. A critical factor, then, is whether or not load tests on a pile or piles are to be implemented for the project. If so, the tests should be performed as early in the design process as possible.

The idea of limit states was introduced 40 years ago and provides the engineer with a basis in considering the factor of safety. Table 8.1 presents a version of the limit states for a pile under axial and lateral loading. Two

TABLE 8.1 Limit States for a Pile Subjected to Axial and Lateral Loading

Ultimate Limit States	Most Probable Conditions
Sudden punching failure under axial loading of individual piles	Pile bearing on thin stratum of hard material
Progressive failure under axial loading of individual piles	Overloading of soil in side resistance and end bearing
Failure under lateral loading of individual piles	Development of a plastic hinge in the pile
Structural failure of individual piles	Overstressing due to a combination of loads; failure of buckling due principally to axial load
Sudden failure of the foundation of the structure	Extreme loading due to earthquake causing liquefaction or other large deformations; loading on a marine structure from a major storm or an underwater slide
Serviceability Limit States	
Excessive axial deformation	Design of large-diameter pile in end bearing on compressible soils
Excessive lateral deformation	Design with incorrect *p-y* curves; incorrect assumption about pile-head restraint
Excessive rotation of foundation	Failure to account for the effect of inclined and eccentric loading
Excessive vibration	Foundation too flexible for vibratory loads
Heave of foundation	Installation in expansive soils
Deterioraton of piles in the foundation	Failure to account for aggressive water; poor construction
Loss of esthetic characteristics	Failure to perform maintenance

Source: From Reese and Van Impe, 2001.

categories are presented: ultimate limit states and serviceability limit states. A collapse is considered in the first instance and the ability of the pile to perform acceptably in the second instance. While the table is not comprehensive, the engineer will find the concept of limit states useful in considering a particular design.

The factor of safety for the foundations of a project may be selected with a consideration of limit states, with the data at hand for use in the design, and after evaluation of the quality of the data. Constraints imposed by the building code must be taken into account. Two approaches are in use: selection of a global factor of safety and selection of a partial factor of safety. Both methods are discussed below.

8.6.1 Selection of a Global Factor of Safety

The first approach is to employ a global factor of safety that is normally used to augment the loads on a structure. For the design of a pile under lateral load, the working loads are augmented until the pile fails by the development of a plastic hinge or experiences excessive deflection. The global factor of safety is the load at failure divided by the working load, where the working load is that which is experienced by the structure during its regular use.

Is is convenient to consider the loads on the structure and the resistances supplied by the foundation to be time dependent, as shown in Figure 8.1.

The loads will vary with time as floor loads change and as the structure is subjected to wind and possibly waves. The resistance can vary as pore pressure dissipates around driven piles and as the water content changes in near-surface clays. The global factor of safety can be expressed in Eq. 8.1:

$$F_c = m_R / m_S \tag{8.1}$$

where

F_c = global factor of safety,
m_R = mean value of resistance R, and
m_S = mean value of loads S.

While producing the curves shown in Figure 8.1 may not be possible, the engineer considers all of the factors affecting the loads and resistances and arrives at values using best judgment to avoid the crosshatched area shown in the figure.

Values of the relevant soil parameters in a report on the subsurface investigation invariably reveal significant scatter as a function of depth. The usual

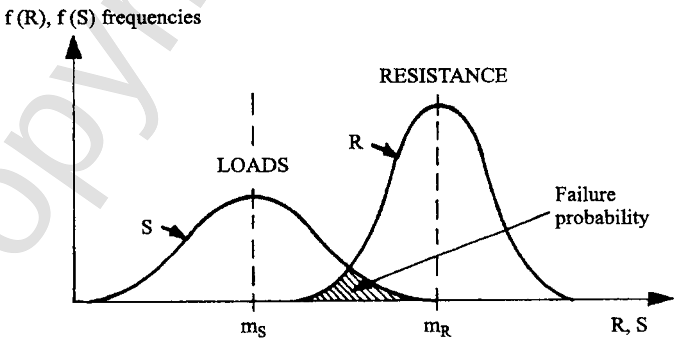

Figure 8.1 Probability frequencies of loads and resistance (from Reese and Van Impe, 2001).

approach is to select average values with depth, perhaps erring on the low side. The analyses are made with service loads and then augmented loads. The engineer then uses judgment to decide if the global factor of safety being employed is adequate for the project.

Another procedure is to select lower-bound values of soil resistance with the service loads augmented to obtain failure due to either overstressing a component of the foundation or due to excessive deflection. If the global factor of safety is adequate with the use of lower-bound soil properties, the engineer may have confidence in the design. However, for a large project, the potential savings on construction may be sufficient to justify full-scale testing of prototype foundations in the field.

8.6.2 Selection of Partial Factors of Safety

The second approach is implemented by the method of partial safety factors. The resistance R^* may be modified as shown in Eq. 8.2:

$$R^* = \frac{r_m}{\gamma_m \gamma_f \gamma_p} \tag{8.2}$$

where

r_m = mean resistance or strength,
γ_m = partial safety factor to reduce the strength of the material to a safe value,
γ_f = partial safety factor to account for deficiencies in fabrication or construction, and
γ_p = partial safety factor to account for inadequacies in the theory or model for design.

The loading S^* may be modified as shown in Eq. 8.3:

$$S^* = s_m \gamma_1 \gamma_2 \tag{8.3}$$

where

s_m = mean value of load,
γ_1 = partial load factor to ensure a safe level of loading, and
γ_2 = partial load factor to account for any modifications during construction, effects of temperature, and effects of creep.

Using the partial safety factors in Eqs. 8.2 and 8.3, a global factor of safety may be computed as shown in Eq. 8.4:

$$F_c = (\gamma_m \gamma_f \gamma_p)(\gamma_1 \gamma_2) \tag{8.4}$$

The method of partial safety factors may be formally implemented by selecting values from a set of recommendations by a building authority based on poor control, normal control, or good control. The engineer who uses the formal approach to development of a factor of safety can employ values for the factors shown in Eq. 8.4 but must also use judgment in giving specific values to the terms in the equation. If an informal approach to selecting the global factor of safety for a given foundation is employed, the factors in Eq. 8.4 provide a useful guide.

The American Association of State Highway and Transportation Officials (AASHTO) adopted a method in 1994 based on modification of load and resistance factors (LRFD), similar in concept to the method of partial safety factors. LRFD is discussed in numerous articles and reports in the current literature.

8.7 DESIGN PROCESS

A design can be made with the following information at hand: type of foundation; nature and magnitude of loads; constraints on movement, both initial and final; results from the soil investigation; quality of the soil investigation; analytical model along with computer code; nature of the structure and the effects of a failure; and all other factors affecting the selection of a factor of safety. Figure 8.2 shows an engineer at work with a computer. The analyses and design are carried out in such a manner that a review can be made with a full understanding of the assumptions and the results of all computations.

The computer has an important role. Computer codes exist for the solution of many problems, as noted in many of the chapters in this book. Two characteristics define the computer: (1) results can be obtained so rapidly, even for nonlinear problems where iteration is required, that the influence of many parameters on a solution can be investigated with little effort by the engineer; (2) the results from a computer solution may be incorrect. In regard to the first item, rarely does a soil report fail to show scatter in the results of soil properties. The usual procedure is to employ average values, with some leaning toward lower values. However, the engineer can easily compare results from selection of lower-bound values, upper-bound values, and average values.

However, in view of the second item, the engineer must be prepared to check the results of a computer solution. Usually, the results can be easily checked to see that the equations of static equilibrium are satisfied. Even for nonlinear problems, some checks can be made with hand computations to investigate correctness. Such checks of the computer results should be indicated in the written material that accompanies the report on design.

Figure 8.2 View of an engineer at work.

In the course of an analysis, close interaction between the various engineers is necessary, particularly between the geotechnical and structural engineers. Frequently, the final design is continuing and significant changes may have been made that affect the design of the foundations. Furthermore, the decision may be made to prepare alternate designs for submittal in the contract documents in order to achieve the lowest cost for the project.

Appendix 8.1 presents a list of considerations that can lead to improved designs. The aim is to create a design that is understood by the contractor and that is relatively easy to construct.

8.8 SPECIFICATIONS AND INSPECTION OF THE PROJECT

The preparation of specifications should be considered an important area of work for the engineer. Many firms will have a computer file containing specifications for the construction of various kinds of foundations. Using such information without careful consideration of the job at hand is unwise. Methods of construction change, and new ways of performing work are constantly being developed. The Internet can be used to pull up specifications by some agencies of contractors, and other sources may have specifications that can be examined. The writers have spoken to contractors who have discovered defective specifications in bid documents but refrained from comment for a variety of reasons. However, dealing with defective specifications after a job has begun is always difficult.

Details that are important in achieving good construction may be easy to overlook. For example, concrete for drilled shafts is poured with a tremie after the rebar cage has been placed. The design of the concrete is critical to ensure that it fills the entire excavation and develops an appropriate pressure value at the interface with the soil. A feature that is sometimes overlooked is that the spacing between rebars must be adequate to allow free passage of the concrete, depending on the maximum size of the coarse aggregate in the mix. Ample guidance exists here and in the literature on construction of drilled shafts to assist the engineer in sizing the spaces between rebars.

After construction has been completed, the engineer should take advantage of the contractor's knowledge to ask how the design and specifications could have been improved to achieve better construction. Such interaction between the engineer and the contractor is generally not possible during the bidding phase of the project, but it can be extremely valuable after the job has been completed.

Inspection of the construction of the foundations frequently is a gray area. Sometimes a special firm is employed by the owner to perform all of the inspection. However, the geotechnical engineer should take all desirable steps to ensure that the foundations are inspected by a firm that is fully knowledgeable about their design and about the specifications that have been prepared. Some geotechnical firm insist on inspecting the foundations they have designed.

8.9 OBSERVATION OF THE COMPLETED STRUCTURE

Far too few detailed observations have been made of completed structures, but the *observational method* is employed in some countries. With the permission of the owner, perhaps a governmental agency, a design is completed with the understanding that the behavior of the structure will be observed over time. If the structure shows some deficiency, such as total or differential settlement, provisions are made in the design to allow strengthening of the structure. Such a method is unusual.

One of the authors wished to install instruments at the base of the raft foundation for a high-rise building. The instruments would have allowed pressures and movements to be measured, providing insight into the response of the soil and the assumptions made in the design of the raft. A dinner was held in a luxurious club, and the architect and engineers came from a distant city. The research proposal was made, and a representative of the owner asked, "Is there any danger of failure of the foundation of the building?" "No, absolutely not!" "Then there is no reason for the company to allow the research." Unfortunately, this response was typical, but it was understandable. Engineers, however, should push for the opportunity to instrument candidate structures to gain information to be used in improving methods of design.

PROBLEMS

P8.1. Select no more than three of the items from the ASCE Standard for Professional Conduct of Civil Engineers and write a one-page, single-spaced essay using your word processor. The emphasis will be on your qualifications as a civil engineer.

P8.2. List the 11 items in Appendix 8.1 in the order of their importance to you and write a paragraph about one of them.

P8.3. Look at Chapter 11 and find the recommendation for the space between the rebars in a drilled shaft as related to the maximum size of the coarse aggregate.

APPENDIX 8.1

Considerations to Lead to Improved Designs

1. Communicate well. Written documents, computation sheets, and drawings should be clear and concise. If you have questions about presentation of information, ask a colleague to review your work.
2. Carefully consider complexities that are unusual. Designs are rarely ''run of the mill,'' so deal with technical challenges to the best of your ability.
3. Use the computer as a tool and with judgment. Develop a healthy skepticism about results from computer runs until you have confirmed them by checking.
4. Design by considering tolerances. In practice, for example, piles cannot be installed precisely, so account for some eccentricity in vertical loads.
5. Mistakes are difficult to avoid. An in-house review of your work is essential, and you can encourage your firm to adopt a peer review process by outside designers.
6. Take advantage of the experienced engineers in your firm. Ask questions and solicit ideas on difficult problems.
7. Eagerly tackle jobs for which you are competent; ask for help when your knowledge is weak. Even the most reputable firms ask for help from outside experts when necessary.
8. Make certain that your data are accurate. Making assumptions about features of a problem is unacceptable.
9. View the construction of foundations you have designed. Experience is a great teacher.
10. Consider the ground to be riddled with previous construction. Take all possible steps to locate underground utilities or other obstructions before making final designs.
11. Make lifelong learning a goal in your engineering practice. Attending conferences and workshops and reading technical literature in a field are methods the engineer can use to learn. Such learning should never cease while the engineer continues to practice.